Comparative Medicine
Copyright 2023
by the American Association for Laboratory Animal Science

Vol 73, No 4
August 2023
Pages 323–328

Original Research

CT Evaluation of the Tracheobronchial Tree in Swine

Xiaoyu Gao,[1,†] Ines Antunes,[2] Nile Khai Luu,[2,†] Negin Hadjiabdolhamid,[2] Alesh Ruben Polivka,[2] and Sabee Molloi[2,*]

Swine are commonly used for research on the respiratory system, but various anatomic features of the tracheobronchial tree of swine are poorly defined. The purpose of our study was to acquire normative measurements of the tracheobronchial tree of swine by using chest CT scans, thus laying a foundation for treating or studying airway disorders in this species. In our study, 33 male swine underwent thoracic CT scans; we measured anatomic features of the tracheobronchial tree, including the diameter, length, and angle of various airway structures. We further analyzed the relationships among selected principal parameters. Our data revealed several similarities and differences in anatomy between swine and humans. This information may be useful in future research.

Abbreviations: AP-TD, anteroposterior TD; TD, tracheal diameter; Tr-TD, transverse TD

DOI: 10.30802/AALAS-CM-22-000101

Introduction

Respiratory diseases are among the most important health problems in humans and constitute a fundamental target of teaching and scientific research.[10] The anatomic and physiologic similarities of various organ systems, such as the respiratory system, between swine and humans, combined with the wide availability of swine, make swine useful options for research.[3,4,11] These benefits are especially true for research on airway stents and tracheal intubation.

Although previous overviews describe swine pulmonary anatomy in general, only the tracheaobronchial structures have been described in detail,[8] but data are not available on the diameters, lengths, and angles of various components of the tracheobronchial tree. In addition, species-specific physiologic and anatomic features of the tracheal bronchus of swine have not been described in detail. The purpose of the current study was to determine whether the shape and diameter of the swine trachea is consistent between animals.

Materials and Methods

Ethics statement. The study was approved by the IACUC at the University of California–Irvine (protocol no., AUP-18-191). All experiments were performed under anesthesia, and all efforts were made to minimize animal pain and suffering.

General methods. The study used 33 male Yorkshire pigs (age, 99 ± 15 d; weight, 48 ± 8 kg) (Table 1). Before the start of the experiment, the pigs were fasted for 12 h, with water available. All experimental data were acquired between July 2017 and May 2022 and were analyzed between September 2021 and June 2022. Other organ systems, including the coronary arteries and lungs, have been described previously.[7,14]

Animal preparation. Anesthesia was induced via intramuscular injection of tiletamine–zolazepam (4.4 mg/kg), ketamine (2.2 mg/kg) and xylazine (2.2 mg/kg) and was maintained throughout the study by using 1.5% to 2.5% isoflurane (Highland Medical Equipment, Temecula, CA, and Baxter, Deerfield, IL). The pigs were intubated with a 7.0-mm endotracheal tube and mechanically ventilated during the study. At the end of the experiment, each animal was euthanized by using intravenous KCl injection (1 mL/kg).

CT scanning protocol. Each pig was placed in a supine positio and passed headfirst through the CT gantry (320-slice Aquilion One, Canon Medical Systems, Tustin, CA). The CT parameters were 120 kV; reference tube current, 100–200 mA; rotation time, 0.35 s; collimation, 320 × 0.5 mm. Scanning was performed from the thoracic inlet to the diaphragm. All scans were acquired at full expiration, with the ventilator manually turned off to simulate a breath hold. The volumetric data sets were then transferred to a workstation (version 6.0, Vitrea fX, Vital Images, Minnetonka, MN) for subsequent review. A transverse section (thickness, 0.5 mm) was reformatted into multiplanar reconstruction, minimum density projection, and volume rendered images.

Image analysis and measurements. A senior diagnostic radiologist with 14 y of specialized experience in X-ray, CT, MRI, and other diagnostic imaging techniques, reviewed the scans for technical adequacy and performed the measurements. All images were reviewed by using a Vitrea workstation (version 6.0, Vitrea fX, Vital Images, Minnetonka, MN) that allowed the reviewer to edit CT volume data sets to create optimal 3D CT images of central airways (Figure 1). Tracheal and bronchial measurements were obtained from the images (Figure 2).

Tracheal measurements. The internal diameters of the trachea were measured at 4 levels (that is, TD1, TD2, TD3, TD4) by using axial images on a lung window sequence (Figure 3); these

Submitted: 22 Sep 2022. Revision requested: 01 Nov 2022. Accepted: 27 Mar 2023.
[1]Department of Radiology, Suzhou Health Vocational College, Suzhou City, China, and [2]Department of Radiological Sciences, University of California, Irvine, California
†These authors are co-first authors and contributed equally to the work.
**Corresponding author. Email: symolloi@uci.edu*

Table 1. Weight and age of the 33 male Yorkshire swine evaluated

Animal	Weight (kg)	Age (d)
1	46.5	90
2	44.0	97
3	43.0	83
4	46.0	118
5	53.5	90
6	42.5	111
7	43.5	83
8	44.8	118
9	60.5	99
10	46.0	91
11	41.5	95
12	50.0	97
13	43.0	90
14	44.5	89
15	45.5	90
16	39.5	84
17	53.5	105
18	53.0	102
19	38.0	88
20	39.2	84
21	38.0	81
22	56.0	110
23	51.5	103
24	54.0	116
25	53.0	94
26	57.0	124
27	61.0	108
28	29.0	75
29	61.0	139
30	60.0	129
31	61.0	108
32	47.0	94
33	45.5	96

levels were easily recognizable, and the distance between them was relatively similar. To ensure accuracy, all diameters are expressed as the average of the anteroposterior and transverse measurements. When a swine is supine, the trachea is angled away from horizontal, so accurate anteroposterior measurements cannot be obtained from the original transverse images. To address this problem, we used isotropic imaging with multidetector CT, and the central axis was determined through 3D reconstruction of the airways. The transverse reconstructions were obtained relative to the central axis, thus permitting accurate anteroposterior measurement. Specifically, TD1 was the tracheal diameter at the thoracic inlet level (approximately at the lower edge of the T1 vertebral body); TD2 was the diameter at the level of the aortic arch (approximately at the lower edge of the T2 vertebral body); TD3 was at 2 cm above tracheal carina (approximately at the lower edge of the T3 vertebral body); and TD4 was at the tracheal carina (approximately at the T4 or T5 vertebral body).

The tracheal length in the thorax was measured as the distance between the thoracic inlet and the carina, starting at the first image slice in which both lung apices—but not the laryngotracheal junction—were visible.

The angle between the left and right main bronchi was measured as the angle between the long axis of the right main-stem bronchus and that of the left main stem bronchus.

Bronchial measurements. Bronchial diameters, lengths, and angles were measured based on minimum density projection images.

The diameter of the tracheal bronchus was measured at its opening, and its length was measured as the distance between its opening and the point at which it divides into secondary bronchi. The tracheal bronchus angle was measured as the angle between the long axis of the tracheal bronchus and that of the trachea.

The diameters of the left and right main-stem bronchi were measured at their openings at the tracheal bifurcation; the lengths of the main-stem bronchi were measured as the distance between the tracheal bifurcation and the point where the main-stem bronchus divides into secondary bronchi. The angle

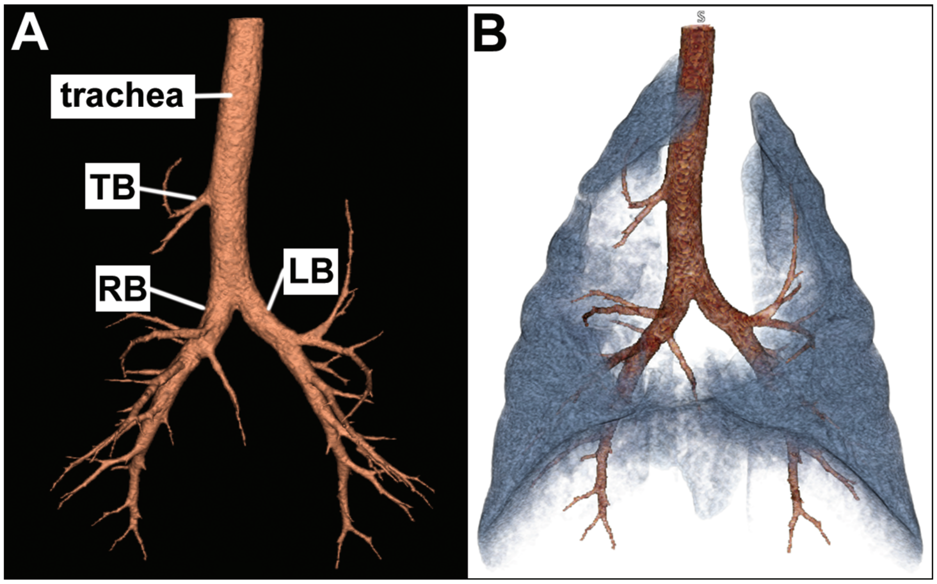

Figure 1. 3D image showing the anatomy of the tracheobronchial tree in swine. (A) The tracheobronchial tree. (B) The tracheobronchial tree with the presence of the lung. LB, left main-stem bronchus; RB, right main-stem bronchus; TB, tracheal bronchus.

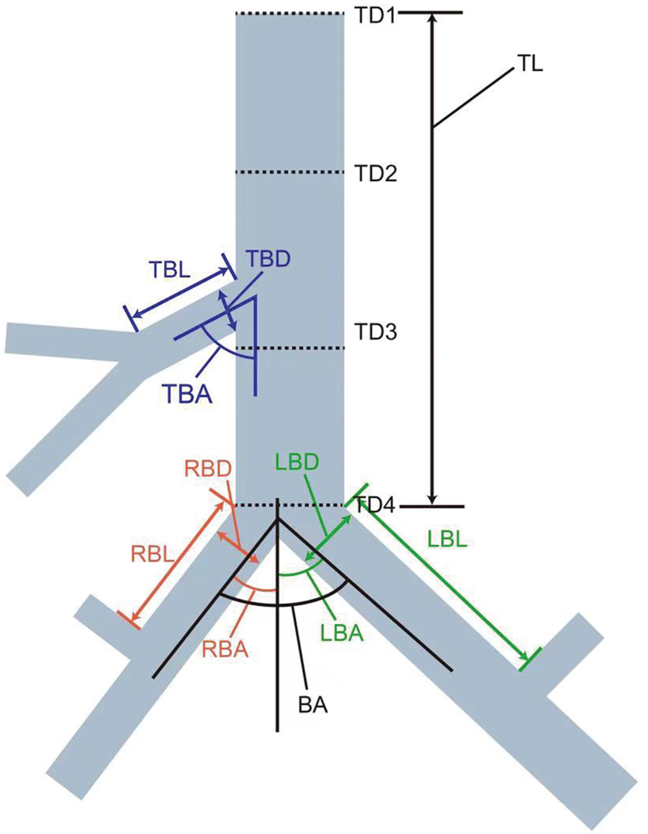

Figure 2. Tracheal and bronchial measurements. BA, angle between left and right main-stem bronchi; LBA, left main-stem bronchus angle); LBD, left main-stem bronchus diameter; LBL, left main-stem bronchus length; RBA, right main-stem bronchus angle); RBD, right main-stem bronchus diameter; RBL, right main-stem bronchus length; TBA, tracheal bronchus angle; TBD, tracheal bronchus diameter; TBL, tracheal bronchus length; TD1, tracheal diameter at the thoracic inlet; TD2, tracheal diameter at the level of the aortic arch; TD3, tracheal diameter at 2 cm above tracheal carina; TD4, tracheal diameter at the tracheal carina; TL, intrathoracic tracheal length.

of the main-stem bronchi were measured between the long axis of the main-stem bronchus and the tracheal bifurcation in the sagittal plane.

Statistical analysis. SPSS version 28.0 (IBM, Armonk, NY) was used for statistical analysis. The radiologist performed each measurement 3 times; each data point represents the mean of these 3 measurements. All data are presented by using descriptive statistics (mean and SD). The internal diameters of the trachea at the 4 levels evaluated were compared by using paired *t* tests (the diameters at the 4 levels were compared in pairs) with Bonferroni correction of α error. Paired *t* tests with Bonferroni correction of α error also were performed for differences in diameter, length, and angle between the 2 groups of left and right main-stem bronchi. Differences were considered statistically significant when the *P* value was less than 0.05.

Results

Anatomic analysis of CT image. Images were analyzed from a total of 33 male Yorkshire swine (Table 1). CT scans were satisfactory in all swine subjects. High-quality 2D multiplanar reformatted images and 3D reconstruction images of the tracheobronchial tree were obtained for all swine. The airways and other organs could be visualized on the CT images. The general morphology of the tracheobronchial tree of swine was similar to that of humans. Tracheal division into the right and left main-stem bronchi occurred at the level of the T4 or T5 vertebra in the decubitus position. The main difference between swine and humans was that the tracheal bronchus of swine arose from the right wall of the trachea, proximal to the tracheal bifurcation (Figure 4). Tracheal bronchi were present in all 33 pigs evaluated.

None of the pigs had any stenosis or endoluminal lesions in the central airways.

Tracheal measurements. Mean tracheal diameters TD1, TD2, TD3, and TD4 were 16.3 ± 1.4, 16.4 ± 1.3, 16.5 ± 1.6, and 16.7 ± 1.4 mm, respectively. The mean tracheal diameter, length, and angle were 16.5 ± 1.4 mm, 94.9 ± 7.7 mm, and 53.0° ± 11.3°, respectively (Table 2).

Bronchial measurements. The mean diameter, length, and angle of the tracheal bronchus were 4.6 ± 0.8 mm, 10.0 ± 2.1 mm, and 42.8° ± 8.0°. For the right main-stem bronchus, these measurements were 11.4 ± 1.5 mm, 17.0 ± 3.2 mm, and 16.6° ± 6.8°; for the left main-stem bronchus, they were 11.4 ± 1.6 mm, 22.9 ± 3.4 mm, and 36.4° ± 6.5°, respectively. The diameters of the right and left main-stem bronchi were not different ($P = 0.915$). Overall, the length and angle of the right main-stem bronchus were smaller ($P = 0.000$) than those of the left bronchus (Table 3).

Discussion

In the field of respiratory medicine, swine have become an important bridge between traditionally used small animal models and human medicine. Pigs are used not only in studies of airway structure but also for respiratory disease and transplantation research. Swine are also becoming increasingly important in the field of interventional pulmonology, where new diagnostic and endobronchial techniques are being developed.

Performing experiments using airway stents requires accurate understanding of the anatomy of the swine trachea. Our current findings indicate that the trachea varied from an elongated oval shape to a horizontal oval, depending on location in the chest. In addition, at the thoracic inlet level and near carina, the trachea was transversely oval in shape. However, at the aortic arch and 2 cm above carina, the shape was circular or near-circular (Figure 3). These variations may reflect differences in blood vessel pulsation or intrathoracic pressure. Although the ventilator was turned off the ventilator during scan acquisition to mimic apnea, some air may have entered the lungs regardless and thus led to differences in chest pressure and traction forces on the trachea. However, the external force at the thoracic inlet and carina remained the same, thus explaining the consistent shape of the trachea in these locations. In addition, TD4 was different from TD1 but not from TD2. Furthermore the diameter of the trachea increased gradually from Cranial to caudal, consistent with some previous reports[2] but not others that found no appreciable changes in the diameter of the trachea from the thoracic inlet to the upper carina.[5,6]

Swine have been extensively used in many areas of research, especially cardiovascular disease [7,14] and organ transplantation.[13] Nevertheless, only a few studies that used radiologic methods mention anatomic descriptions of the respiratory system.[1,3,13,14] To our knowledge, the current study is the first to measure anatomic parameters of the swine tracheal bronchus, which arises from the right wall of the trachea, in contrast to humans, who do not have a tracheal bronchus. In addition, we have identified a lack of consensus regarding the anatomic description and name of the tracheal bronchus. A previous report[8] described the tracheal bronchus as a secondary bronchus of the right main-stem bronchus and labeled it as RB1 (the first bronchiole of the right main-stem bronchus). Other reports[1,3] considered that the tracheal bronchus originates

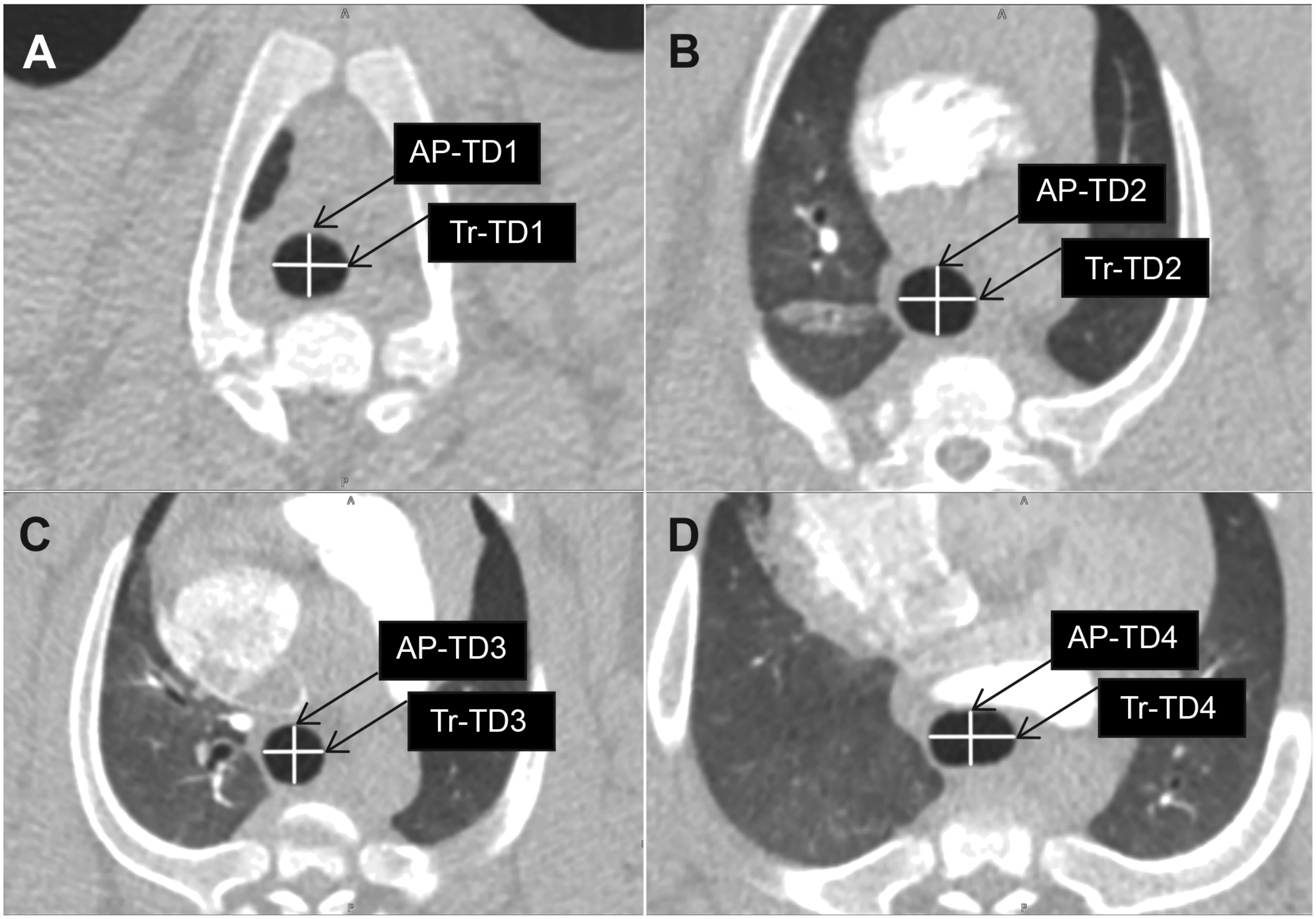

Figure 3. Measurements of the diameter and angle by using the axial images of a lung window CT sequence at 4 levels. (A) TD1 = (AP-TD1 + Tr-TD1) / 2. (B) TD2 = (AP-TD2 + Tr-TD2) / 2. (C) TD3 = (AP-TD3 + Tr-TD3) / 2. (D) TD4 = (AP-TD4 + Tr-TD4) / 2. AP, anteroposterior measurement; Tr, transverse measurement; see Figure 2 for all other definitions of abbreviations.

from the side of the trachea, corresponding to the right cranial lobe bronchiole III of the mammalian bronchial tree or that the right cranial bronchus originates directly from the trachea. However, similar to humans, the largest tracheal dimensions in swine are near bifurcations. Specifically, at the main bronchi and carina bifurcation, central airway dimensions are greater, likely due to the division of the airways into 2 branches.[9] According to our data, the length of the trachea was 94.9 ± 7.7 mm, whereas previous reports measured tracheal lengths of 150 to 200 mm.[3,8] This difference might reflect the start site for measuring tracheal length, which usually is the beginning of the laryngotracheal junction. However, our measurements

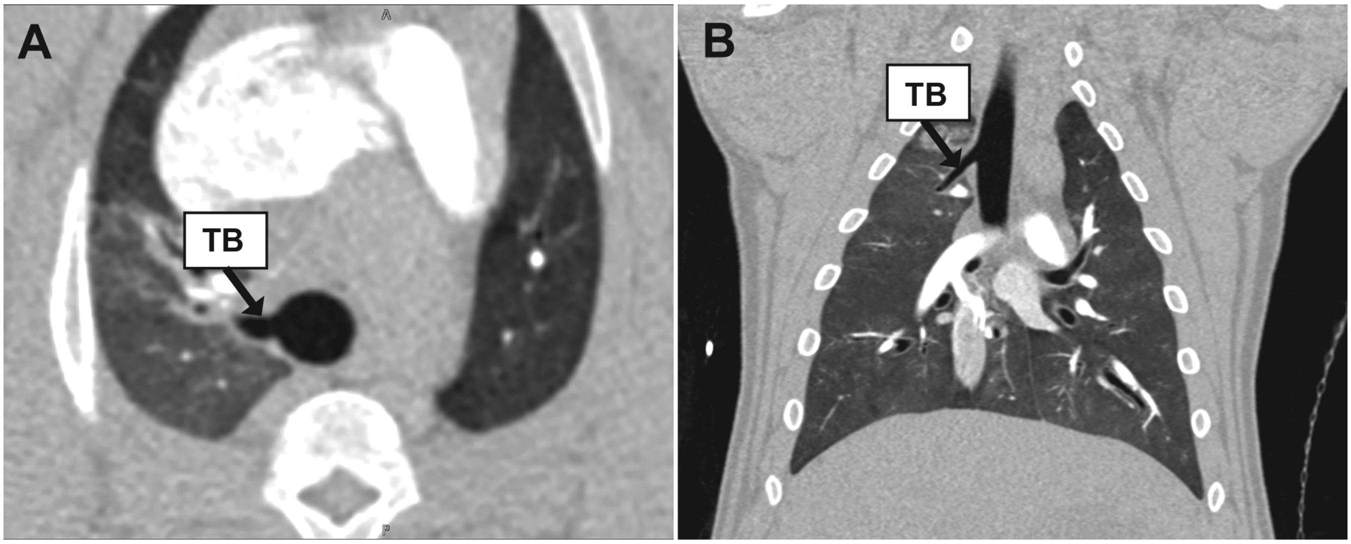

Figure 4. (A) Axial and (B) coronary CT images of the tracheal bronchus (TB) in a pig show details of this structure.

Table 2. Diameter of the swine trachea at 4 levels

	Diameter (mm)
TD1	
Anteroposterior	15.39 ± 1.61
Transverse	17.22 ± 1.42
Overall	16.3 ± 1.4
TD2	
Anteroposterior	16.30 ± 1.40
Transverse	16.52 ± 1.17
Overall	16.4 ± 1.3
TD3	
Anteroposterior	16.16 ± 1.65
Transverse	16.89 ± 1.66
Overall	16.5 ± 1.6
TD4	
Anteroposterior	13.82 ± 1.31
Transverse	19.53 ± 1.93
Overall	16.7 ± 1.4
Overall anteroposterior diameter	15.42 ± 1.78
Overall transverse diameter	17.54 ± 1.95

TD1, tracheal diameter at the thoracic inlet; TD2, diameter at the level of the aortic arch; TD3, diameter at 2 cm above the level of tracheal carina; TD4, diameter at tracheal carina
Values shown are the mean ± 1 SD of 33 swine.

Table 3. Measurements of the tracheal bronchus and the two main stem bronchus of swine

	Diameter (mm)	Length (mm)	Angle (°)
Tracheal bronchus	4.58 ± 0.84	10.00 ± 2.10	42.78 ± 7.98
Main stem bronchus			
Left	11.43 ± 1.63	22.87 ± 3.39	36.45 ± 6.47
Right	11.41 ± 1.47	16.98 ± 3.16	16.58 ± 6.75
P	0.915	0.000*	0.000*

Values shown are the mean ± 1 SD of 33 swine.
*$p < 0.05$.

involved the intrathoracic trachea, starting at the thoracic inlet at the level of the T1 vertebrae.

With regard to bronchial measurements, we confirmed that the airway geometry of swine is similar to that in humans (Figure 5), consistent with previous studies.[1,3,4,8,11] The length and angle of the right main-stem bronchus were smaller than those of the left bronchus, suggesting that the right bronchi are shorter and steeper than the left main-stem bronchus. Similar findings have been reported in humans.[12]

Our study has several limitations. First, our findings do not apply to all swine but apply only to swine of the same sex, breed, and size (male, Yorkshire, 40 to 50 kg), with a mean age of 99 ± 15 d and mean weight of 48 ± 8 kg. Second, we were unable to measure the entire trachea starting from the vocal cords because this region was frequently outside the CT scanning range. Therefore, we focused on the intrathoracic length of the trachea. Last, we did not collect information on the pigs' height, body mass index, or size of the chest, all of which can influence central airway dimensions. Further analysis of the morphologic parameters in swine of various heights, weights, body mass indexes, sexes, and breeds are needed and could indicate whether our results apply to other types of swine.

Figure 5. 3D image of the human tracheobronchial tree.

Some of the strengths of this study are our strict selection criteria and our evaluation of a moderately large number of live and healthy swine. Second, we were able to completely exclude underlying potentially pathologic changes involving central airways. Third, the study was systematic; CT scans were acquired by using a standardized protocol for acquisition, resulting in similar image qualities and yielding accurate reference values. Finally, a high-quality CT scanner was used to obtain high-quality 2D multiplanar reformatted images and 3D reconstruction images of the tracheobronchial tree of swine. We used CT for our study because it is a noninvasive imaging method, has high spatial resolution and short examination time, can clearly display the airway, and accurately determines the location and severity of a lesion. In addition, CT supports a variety of postprocessing technologies (for example, multiplane reconstruction, minimum density projection reconstruction) that are widely used in clinical settings. More specifically, the multislice spiral CT scanner we used (320-slice Aquilion One, Canon Medical Systems) has high temporal resolution that minimizes motion artifacts caused by breathing. Moreover, this instrument obtains high-quality multisurface and 3D reconstruction images, thus increasing the accuracy of measurements.

The growing use of swine in medical research underlies the importance of understanding the basic biologic data of this species. Although considerable data have been accumulated on the anatomy of swine, data derived from living animals are sparse. The findings of this study likely will help researchers who use swine to select the appropriate catheter type and predict the depth of intubation when conducting tracheal intubation. Our study also provides anatomic parameters for the development of swine airway stents.

In conclusion, we obtained normative anatomic CT data for the tracheobronchial tree of swine, particularly of the tracheal bronchus. The results of this study may be helpful in selecting an appropriate catheter and predicting the depth of intubation for pigs. In addition, our results may provide information useful in the development of airway stents for swine.

Acknowledgments

The study was supported by the Radiology Science Department of University of California–Irvine and Jiangsu Overseas Visiting Scholar Program for University Prominent Young and Middle-aged Teachers and Presidents.

References

1. **Castro MGB, Varble NA, Yung RC, Wood BJ, Karanian JW, Pritchard WF.** 2020. In vivo characterization of the swine airway morphometry and motion based on computed tomographic imaging during respiration. J Biomech Eng **142**:121009. https://doi.org/10.1115/1.4047550.
2. **Chen SJ, Shih TT, Liu KL, Chiu IS, Wu MH, Chen HY, Lee WJ.** 2004. Measurement of tracheal size in children with congenital heart disease by computed tomography. Ann Thorac Surg **77**:1216–1221. https://doi.org/10.1016/j.athoracsur.2003.08.002.
3. **Dondelinger RF, Ghysels MP, Brisbois D, Donkers E, Snaps FR, Saunders J, Deviere J.** 1998. Relevant radiological anatomy of the pig as a training model in interventional radiology. Eur Radiol **8**:1254–1273. https://doi.org/10.1007/s003300050545.
4. **Góes AMO, Chaves RHF, Furlaneto IP, Rodrigues EM, de Albuquerque FBA, Smit JHA, de Oliveira CP, Abib SCV.** 2021. Comparative angiotomographic study of swine vascular anatomy: contributions to research and training models in vascular and endovascular surgery. J Vasc Bras **20**:e20200086.
5. **Griscom NT.** 1983. Cross-sectional shape of the child's trachea by computed tomography. AJR Am J Roentgenol **140**:1103–1106. https://doi.org/10.2214/ajr.140.6.1103.
6. **Griscom NT, Wohl ME.** 1986. Dimensions of the growing trachea related to age and gender. AJR Am J Roentgenol **146**:233–237. https://doi.org/10.2214/ajr.146.2.233.
7. **Hubbard L, Malkasian S, Zhao Y, Abbona P, Molloi S.** 2019. Contrast-to-noise ratio optimization in coronary computed tomography angiography: Validation in a swine model. Acad Radiol **26**:e115–e125. https://doi.org/10.1016/j.acra.2018.06.026.
8. **Judge EP, Hughes JM, Egan JJ, Maguire M, Molloy EL, O'Dea S.** 2014. Anatomy and bronchoscopy of the porcine lung. A model for translational respiratory medicine. Am J Respir Cell Mol Biol **51**:334–343. https://doi.org/10.1165/rcmb.2013-0453TR.
9. **Kuo W, Ciet P, Andrinopoulou ER, Chen Y, Pullens B, Garcia-Peña P, Fleck RJ, Paoletti M, McCartin M, Vermeulen F, Morana G, Lee EY, Tiddens H.** 2018. Reference values for central airway dimensions on CT images of children and adolescents. AJR Am J Roentgenol **210**:423–430. https://doi.org/10.2214/AJR.17.18597.
10. **Shukla SD, Vanka KS, Chavelier A, Shastri MD, Tambuwala MM, Bakshi HA, Pabreja K, Mahmood MQ, O'toole RF.** 2020. Chapter 1. Chronic respiratory diseases: An introduction and need for novel drug delivery approaches, p 1–31. In: Dua K, Hansbro PM, Wadhwa R, Haghi M, Pont LG, Williams KA, **eds.** Targeting chronic inflammatory lung diseases using advanced drug delivery systems. San Diego (CA): Academic Press. https://doi.org/10.1016/C2019-0-01427-6.
11. **Smit JHA, Leonardi EP, Chaves RHF, Furlaneto IP, Silva C, Abib SCV, Góes AMO Jr.** 2020. Image-guided study of swine anatomy as a tool for urologic surgery research and training. Acta Cir Bras **35**:e351208. https://doi.org/10.1590/acb351208.
12. **Standring S.** 2020. Gray's anatomy: The anatomical basis of clinical practice, 42nd edition. Philadelphia (PA): Elsevier.
13. **Yoon W, Ryu JM, Lee MY, Moon YJ, Lee SH, Park JH, Yun SP, Jang MW, Park SS, Han HJ.** 2010. 64-channel multi-detector row CT angiographic evaluation of the micropigs for potential living donor lung transplantation. J Vet Sci **11**:185–189. https://doi.org/10.4142/jvs.2010.11.3.185.
14. **Zhao Y, Hubbard L, Malkasian S, Abbona P, Molloi S.** 2020. Dynamic pulmonary CT perfusion using first-pass analysis technique with only 2 volume scans: Validation in a swine model. PLoS One **15**:e0228110. https://doi.org/10.1371/journal.pone.0228110.